NASA Technical Memorandum 82604

(NASA-TM-82604) THE EFFECT OF MINORITY CARRIER MOBILITY VARIATIONS ON SOLAR CELL SPECTRAL RESPONSE (NASA) 12 p HC A02/MF A01 CSCL 10A
N81-23625
Unclas
G3/44 42400

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Prepared for the
Fifteenth Photovoltaic Specialists Conference
sponsored by the Institute of Electrical and Electronics Engineers
Kissimmee, Florida, May 12-15, 1981

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ABSTRACT

Analysis of multi-step diffused, high voltage 0.1 ohm-cm solar cells suggests that the increased voltage capability of these cells is correlated with localized variations in the base minority carrier mobility. An attempt to calculate the behavior of those cells has revealed some unexpected results. It has been shown, contrary to what might have been expected, that spatial variations in the mobility can effect severe changes in the short-circuit current and the spectral response. Variations in cell output as a result of imposing abrupt, linear, and exponential mobility variations are presented.

INTRODUCTION

Recent efforts at the Lewis Research Center have resulted in significant increases in the open-circuit voltage of 0.1 ohm-cm p-base silicon solar cells (1). The improved performance has been achieved through the use of a multi-step diffusion (MSD) technique. Analysis of the charactaeristics of the MSD cell indicates that the increased voltage is due to a reduction in the electron mobility in the cell base (2). It has been postulated that piezoresistive effects caused by diffusion-induced lattice stresses result in localized regions of lower-than-expected electron mobility near the junction in the base. In the course of our investigations, a versatile semiconductor device computer program developed by Hauser and Dunbar (3) for solar cell application was used to model the proposed structures. Since the parametric variations considered here could not be handled through closed form solution of the device equations, this program which simultaneously solves Poisson's equation and the electron and hole quisi-Fermi level equations was used to provide an accurate numerical solution without limiting assumptions or approximations. These calculations have yielded some unexpected results which are reported here.

It is well known that the minority carrier mobility in the cell base plays an important role in determining the cell open-circuit voltage through its effect on the saturation current. The short-circuit current and the spectral response, on the other hand, can easily be shown to be independent of the base mobility as long as the rear surface recombination velocity differs from the diffusion velocity by several orders of magnitude (4). When this condition is met, the mobility terms drop out of the equations and the base mobility has no influence on either the short-circuit current or the spectral response.

In the course of the present work we found that the above statement is not valid if a spatial mobility variation exists in the base. We have found, further, that it is not the magnitude of the mobility that affects the cell output, but rather its degree of change. That is, we find that for a cell with an abrupt change in mobility, from a value μ_1 to a value μ_2 that occurs somewhere between the junction and the rear contact, the current and spectral response are determined by the ratio μ_1/μ_2 and are independent of the absolute values of μ_1 and μ_2.

The purpose of this paper is to present the details of our spectral response calculations for a variety of minority carrier mobility variations. The mobility profiles considered include abrupt, linear, and exponential changes as well as some combinations of these. While the major thrust will be to determine cell output as a function of base changes, a few calculations to determine the effects of mobility variations in a field-free emitter cell will be presented. Also presented are the results of a series of emitter etching experiments which illustrate the use of mobility variation calculations in explaining unexpected spectral response behavior in high voltage MSD cells.

General Model

As stated in the INTRODUCTION, the major part of this work is concerned with the effects of base mobility changes. These calculations were performed on a typical Lewis MSD cell since it is for this type of cell that we have evidence of spatial mobility variations in the base. The parameters used in the calculations are listed in table I. For the emitter calculations we wanted to work with a cell which would illustrate the effects of mobility changes without the complexities introduced by the presence of electric fields. We therefore chose a cell with a homogeneously doped emitter and a deep junction. The values of the parameters used in the calculations are given in table I. It should be noted that these parameters are similar to those found in the University of Florida's high-low-emitter (HLE) cell (5).

Base Mobility Variations

Abrupt variation. - The first case to be considered is the abrupt or step change. As shown in figure 1 we will assume that a sudden change in the mobility occurs at a distance, w, from the junction. The mobility ratio will be defined as μ_2/μ_1 where μ_1 is the near-junction value. Only the mobility ratio will be referred to in what follows because calculations show the results to be independent of the absolute mobility values used.

If, for the MSD cell of table I, we assume a mobility ratio of 10 and calculate the effect of varying the low mobility region width, w, we obtain the series of curves shown in figure 2.

As would be expected, the short wavelength response is not affected by these changes in the base mobility. The long wavelength response, on the other hand, shows a dramatic decrease as w is increased from 0 to about 20 µm. For further increases in w the red response passes through a minimum and begins to rise. As w approaches 165 µm (the base width) the entire curve approaches the values it had when $w = 0$. That these two spectral response curves ($w = 0$ and $w = 165$ µm) are identical illustrates the fact that the spectral response of a homogeneous base cell is independent of the value of the mobility therein. Also, to illustrate the fact that the spectral response is dependent only on the mobility ratio and not on the absolute values used, the calculations of figure 2 were repeated using widely varying values of mobility while maintaining a ratio of 10. The results in each case were identical to those in the figure.

As shown in figure 3, changes occurring close to the junction have a strong effect on the 0.9 µm response. The presence of a 10 µm wide layer of reduced mobility is sufficient to reduce the 0.9 µm response by 40%. Also plotted in figure 3 is the effect of increasing cell thickness to 560 µm. As can be seen, the response shows an overall increase due to the increase in cell volume. The position of the minimum, however, is not affected.

The effect of the mobility ratio on the long wavelength response is shown in figure 4. As can be seen, the higher the mobility ratio, the greater the reduction in response for a given region width. Also, as the mobility ratio increases, the region width for minimum response moves to lower values. Note again the extreme sensitivity of the response to very thin layers of low mobility adjacent to the junction. This sensitivity is accentuated by high mobility ratios. It should be mentioned that the base region adjacent to the junction would be the region most affected by cell fabrication procedures, such as junction diffusion, which have been postulated to cause localized mobility changes (2).

The value of the base diffusion length, L, can also affect the response-width relationship. This is illustrated in figure 5 for a 560 µm thick cell. The lower value of L depresses the response as expected, but it also moves the minimum to lower values of w. In this case the 0.9 µm response drops 25% due to the presence of a low mobility layer ($\mu_2/\mu_1 = 10$) only 5 µm thick.

Up to this point we have been considering the case of a depressed mobility region adjacent to the junction. It should be noted that there also is evidence in the literature supporting the existence of regions of anomalously high mobility (5). For instance, piezoresistive mobility increases in silicon have been observed upon application of a uniaxial compressive stress where the mobility measurements were made normal to stress direction. Let us now consider, therefore, a near-junction region of enhanced mobility. In figure 6 we repeat the calculations of figure 3, but this time for mobility ratios of 0.1 and 0.5. We find, in contrast to the depressed mobility case, that as the high mobility region width is increased the 0.9 µm response increases, passes through a maximum, and finally returns to its original value as w approaches the base width. It appears possible, therefore, to increase the cell current significantly by the insertion of a thin region of enhanced mobility adjacent to the junction.

Linear variation. - The above calculations were performed for an abrupt change in the minority carrier mobility. To determine whether the calculated response variations were due to the abruptness of the mobility change, a set of calculations was performed in which the abrupt change was replaced with a linear variation. Figure 7, for instance, shows the 0.9 µm response variation as a function of the width of the region in which the linear mobility change takes place. Here a physically conservative mobility ratio of 2 was used and the center point of the ramp was fixed at 40 µm from the junction. As can be seen the cell output is insensitive to the transition from the abrupt case ($R = 0$) to the more gently varying linear ramp. For the case considered in figure 7 the results show very little change for ramp widths $\leq$40 µm. It appears, therefore, that the physically-more-meaningful case of a gradual mobility variation from region to region can be closely approximated by an abrupt transition which is much easier to handle analytically. A similar transition behavior was found for the case of an enhanced mobility region near the junction.

Experimental variation. - The effect of replacing the linear ramp with an exponential mobility change is shown in figure 8 where the 0.9 µm response is plotted against the width of the region of lowered mobility. For these calculations the mobility at the depletion region edge was fixed at one-half the value in the high mobility region. We find very close agreement between these data and those computed for linear changes over the same region. The results appear to be insensitive to the details of the spatial variation.

Double step or layer variation. - The final base mobility variation considered involves the insertion of a layer of either enhanced or depressed mobility into an otherwise homogeneous base. Figure 9 shows the variation in cell output as a function of the location of a 10 µm wide region with abrupt boundaries and a mobility one-half that of the surrounding base. Here again it can be seen that the near-junction region is most sensitive to the presence of mobility variations. As the layer is moved toward the rear of the cell, the 0.9 µm response rises to meet and then exceed the homogeneous base value. Similar to the case of an abrupt change, insertion of a layer of enhanced mobility showed essentially the reverse behavior.

As the enhanced mobility region was moved from the junction region to the rear of the cell, the cell output decreased, eventually dropping below that calculated for the homogeneous base case.

Emitter Mobility Variations

Let us now consider the effect of spatial mobility variations in the emitter. In order to compare these results with those of the previous section, it would be desirable to eliminate the complicating presence of electric field effects. We can do this and still work with a physically meaningful cell by using the HLE (3) cell for our model. This cell has a uniformly doped, epitaxially deposited 0.1 ohm-cm emitter, whose surface is passivated with a field layer that reduces its effective surface recombination velocity to low values. The specifics of this call are listed in table I.

Abrupt variation. - This effect of inserting a layer of low mobility (with abrupt boundaries) into the emitter adjacent to the junction is shown in figure 10. In order to amplify the effects of mobility changes we used an arbitrary mobility ratio of 100 in these calculations. As can be seen, the short (0.5 μm) and the long (0.9 μm) responses are affected by changes in the low mobility region width. The short wavelength response is minimized when the emitter is evenly divided into high and low mobility regions regardless of the emitter diffusion length. The long wavelength response, on the other hand, becomes very sensitive to mobility changes occurring near the junction when the emitter diffusion length is less than the emitter thickness.

When we consider the reverse case, that is when the near-junction region has the higher mobility, we find that both the short and long wavelength responses increase and go through maxima as the high mobility region is expanded (fig. 11). As can be seen in the figure, however, this is true only when the emitter diffusion length is small compared to the emitter width. For long diffusion lengths (~80 μm) neither the long nor the short wavelength response is affected by region width changes.

Comparison with Experiment

The Lewis MSD cell is a deep junction device with an inherently low blue response and a less-than-desired short-circuit current. In an effort to increase blue response, the junction depth in several completed cells was reduced by chemically etching the emitter surface between the grid figures. As the junction depth is decreased we would expect a rise in the blue response, no change in the red response, and a rise in total current (2).

The measured variations in current and spectral response at various stages in the etching procedure are shown in figure 12. As can be seen, the blue response increases with junction depth reduction as expected, but the red response and the short-circuit current exhibit severe and unexpected decreases. While we cannot explain this behavior with homogeneous base models, we can get some insight into what is happening by making use of the variable base mobility concept.

If, as has been proposed (1), long diffusions cause stress fields to be propagated into the base from the highly doped and highly stressed emitter, it follows that, when we remove highly stressed emitter regions, we also allow stress relief to occur in the base. In other words, we reduce the width of the low mobility region. If we calculate, then, the variation of the spectral response as the width of the near-junction low mobility region in the base decreases as a result of surface etching, we obtain the set of curves shown in figure 13. In these calculations, an arbitrary mobility ratio of 100:1 was used, and the junction depth was held constant at about 3 micrometers for simplicity. As can be seen the results are quite similar to what was observed experimentally. It thus appears that we can explain the unexpected drop in red response with emitter etching by using a model which relates highly stressed regions in the emitter with regions of lowered minority carrier mobility in the base.

CONCLUSIONS

The major conclusions to be drawn from the preceding analysis are:

1. In contrast to the case of a homogeneous base cell, we have found that the short-circuit current and the spectral response in an inhomogeneous base cell are functions of both the degree and location of the mobility variation.
2. Short-circuit current and spectral response are strongly affected by changes in mobility that occur in a narrow region adjacent to the junction. High mobility ratios and short base diffusion lengths enhance this sensitivity.
3. While variations in the base mobility affect only the long wavelength response, mobility changes in a uniformly doped emitter can effect collection at all wavelengths.
4. Spectral response changes brought on by base mobility variations are insensitive to the abruptness of the mobility variation. Thus the physically-more-realistic case of a gradual mobility change can be closely approximated by an abrupt change which is much easier to handle analytically.
5. Unexpected spectral response changes due to emitter etching in MSD cells can be explained using a mobility variation model.

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TABLE I. - VALUES OF VARIOUS PARAMETERS USED IN CALCULATIONS

	MSD cell	HLE cell
Base		
Doping concentration	1.5×10^{17} cm^{-3}	3.43×10^{17} cm^{-3}
Diffusion length	230 μm	80 μm
Surface recombination velocity	1×10^{6} cm/sec	1×10^{6} cm/sec
Thickness	165 μm	290 μm
Mobility	Variable	550 cm^2/V_{sec}
Emitter		
Doping concentration	5.6×10^{19} ERFC 0.833x	9×10^{16} cm^{-3}
Diffusion length	15 μm	80 μm
Surface recombination velocity	1×10^{6} cm/sec	0 cm/sec
Thickness	2.78 μm	10 μm
Mobility	350 cm^2/V_{sec}	Variable
A. R. coating	None	SiO_2

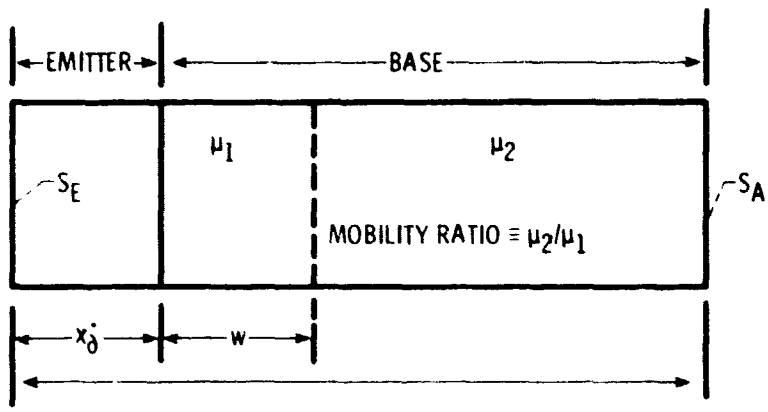

Figure 1. - Schematic identification of parameters used to calculate effects of abrupt mobility variation. See table I.

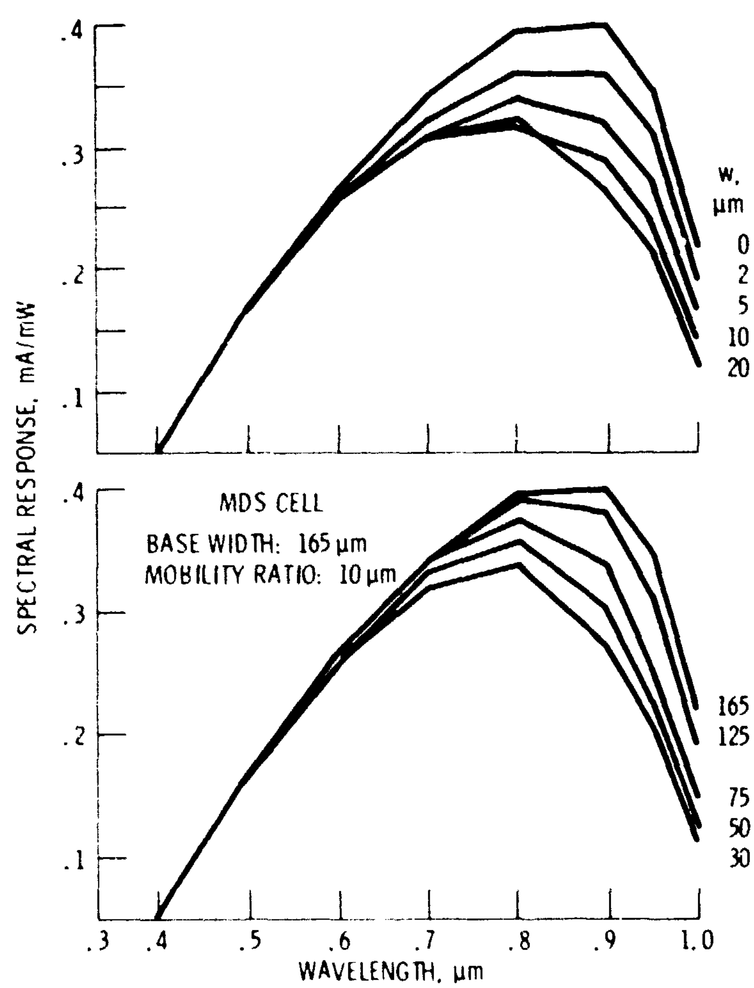

Figure 2. - Variation of spectral response with width of low mobility region.

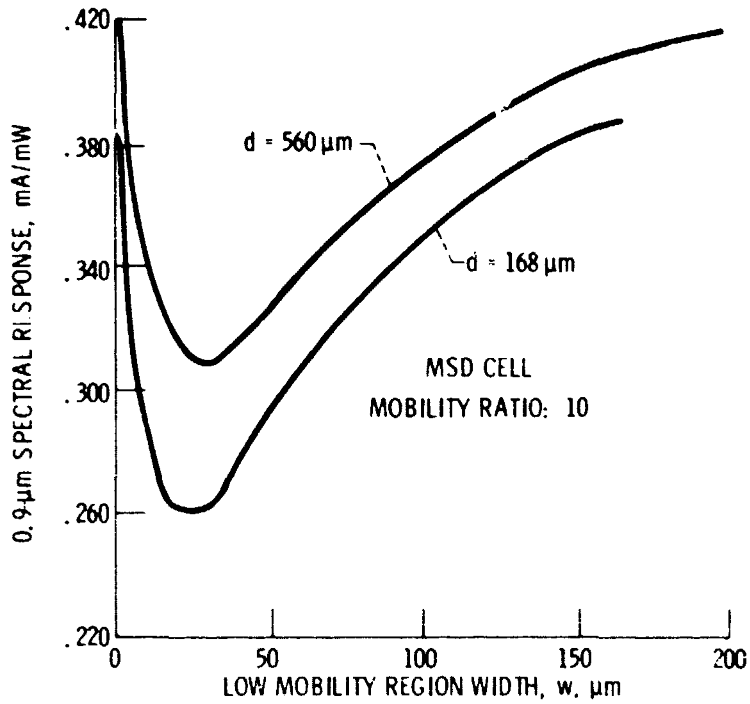

Figure 3. - 0.9 µm response variation with width of low mobility region: effect of cell thickness.

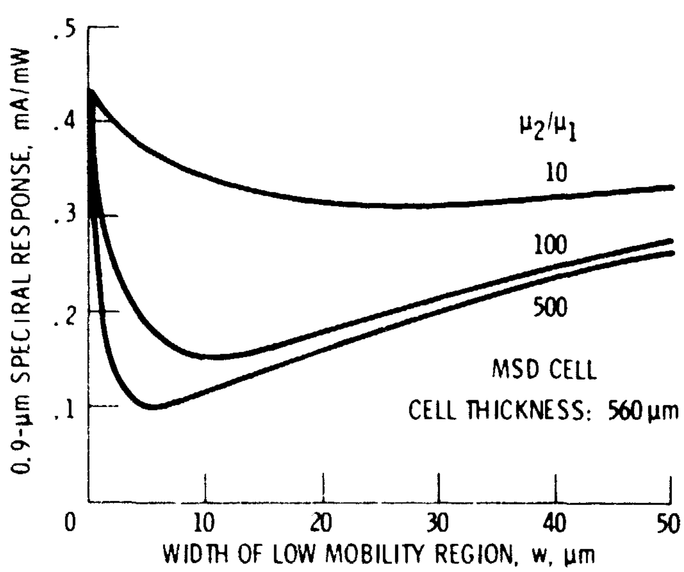

Figure 4. - 0.9-µm response variation with width of low mobility region: effect of mobility ratio.

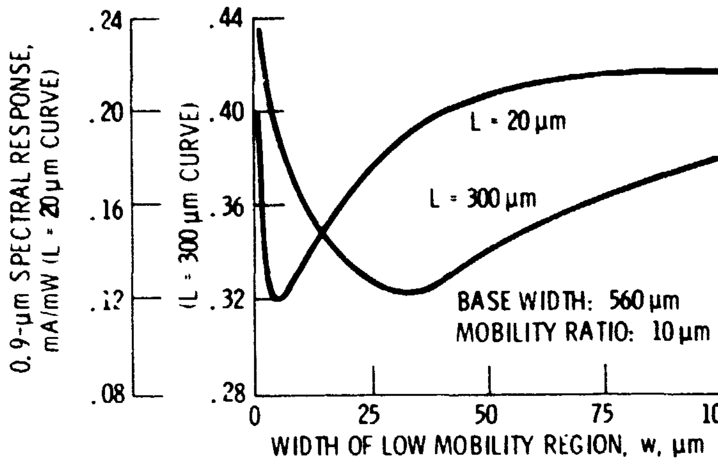

Figure 5. - 0.9-µm response variation with width of low mobility region: effect of base diffusion length.

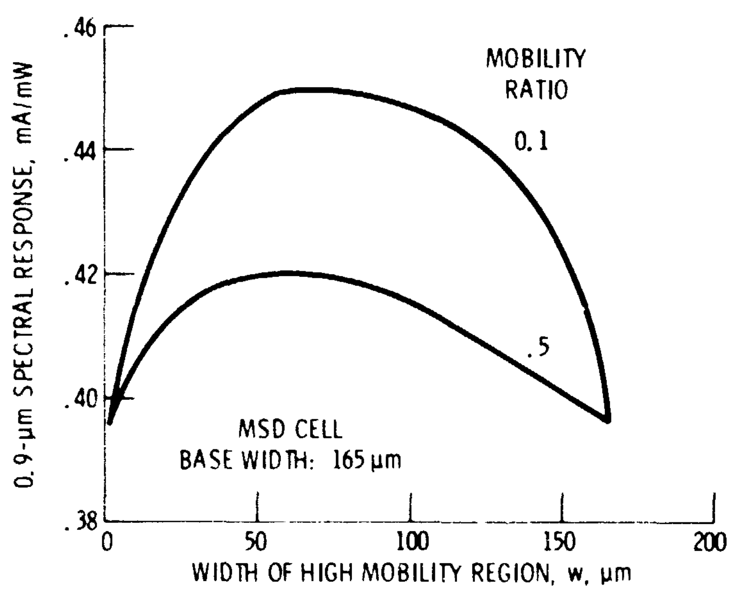

Figure 6. - 0.9-µm response variation with width of high mobility region, w.

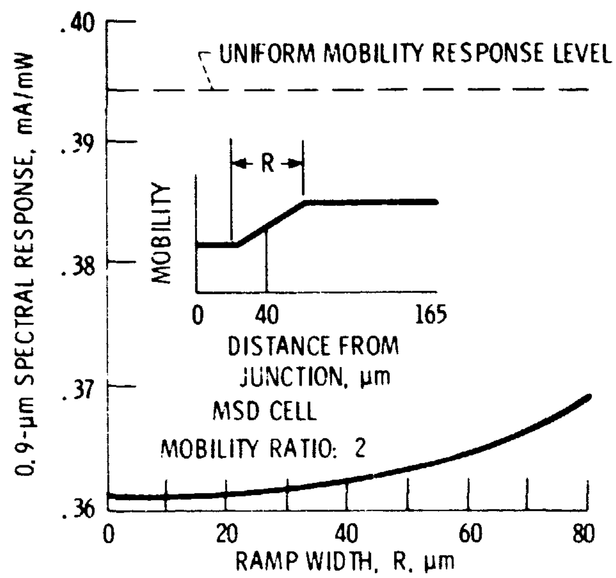

Figure 7. - 0.9-μm response variation with width of linear mobility ramp, R.

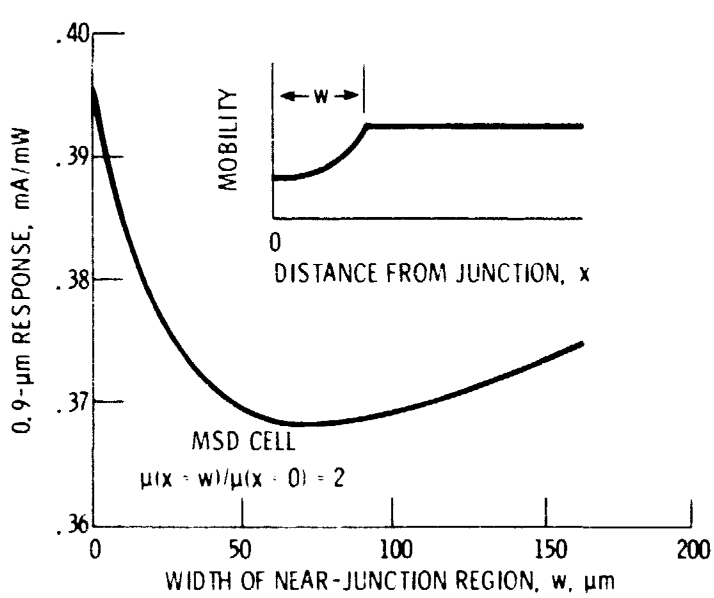

Figure 8. - 0.9-μm response variation with width of region of exponentially changing mobility.

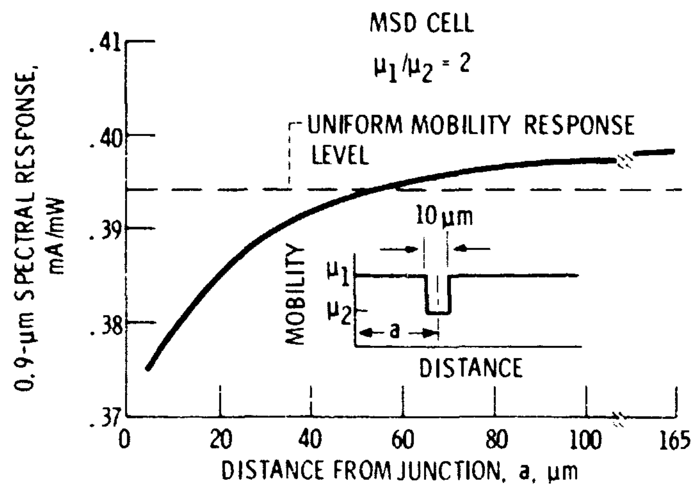

Figure 9. - 0.9-µm response variation with location of low mobility layer.

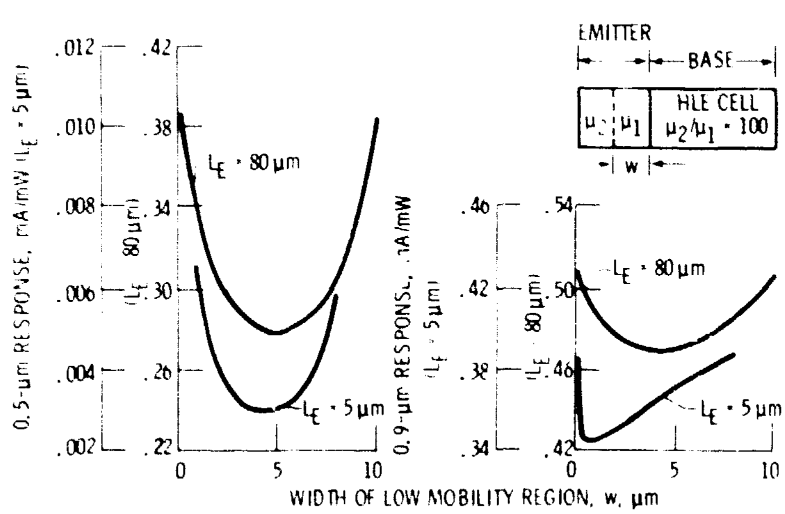

Figure 10. - 0.5- and 0.9-µm response variation with width of low mobility region, w, and emitter diffusion length, L_E.

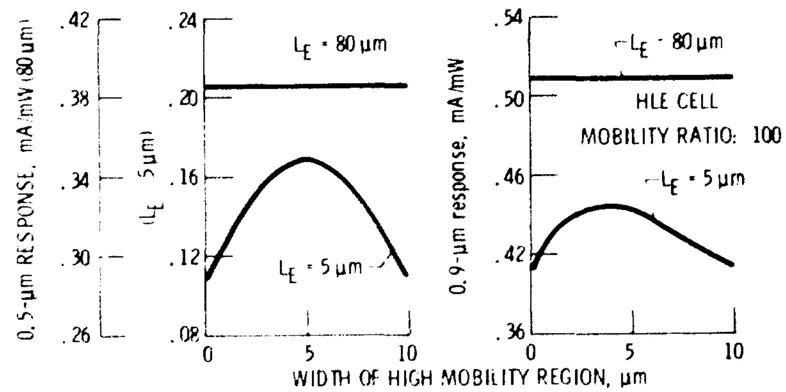

Figure 11. - 0.5- and 0.9-µm response variation width of high mobility region and emitter diffusion length, L_E.

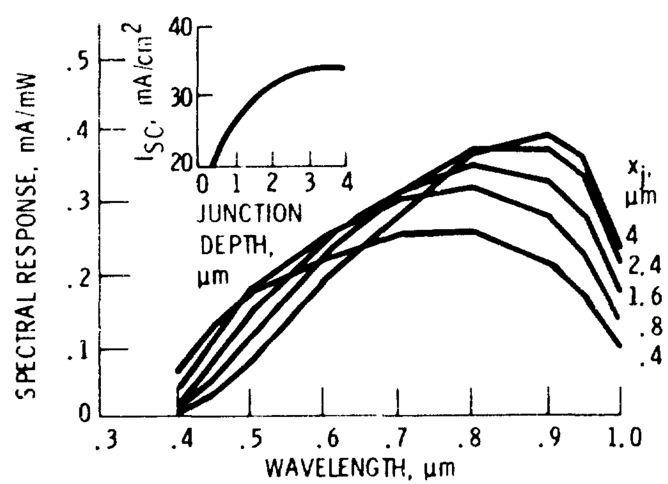

Figure 12. - Current and spectral response measured at various stages during emitter etching experiment.

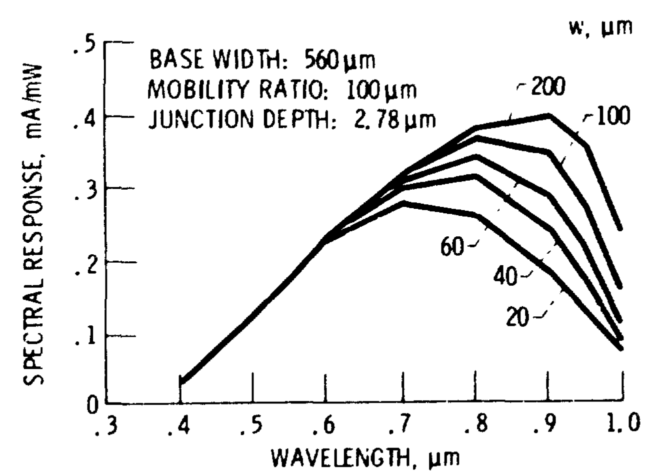

Figure 13. - Calculated variation in spectral response with low mobility region width, w.